REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 28 June 2001	3. REPORT TYPE AND DATES COVERED Final 1 June 1996 - 30 May 2001

4. TITLE AND SUBTITLE

Performance Evaluation of Mobile, Distributed, Direct-Sequence Spread-Spectrum Communication Networks

5. FUNDING NUMBERS

N00014-96-1-0869

6. AUTHOR(S)

Michael B. Pursley and Carl W. Baum

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electrical & Computer Engineering
Clemson University
303 Fluor Daniel Building
Clemson, SC 29634

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 N. Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Research has been completed on the performance of mobile, distributed, spread-spectrum wireless communication networks. New network protocols have been designed, analyzed, and simulated. The protocols are adaptive in order to maintain efficiency in environments with time-varying interference and propagation conditions. Results have been developed and published for adaptive transmission, adaptive forwarding, channel access, and adaptive routing protocols.

14. SUBJECT TERMS

mobile tactical wireless communication networks, spread-spectrum, adaptive protocols

15. NUMBER OF PAGES

5

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Final Report

Title: Performance Evaluation of Mobile Distributed Direct-Sequence
          Spread-Spectrum Communication Networks

ONR Grant Number: N00014-96-1-0869

Principal Investigators:

Michael B. Pursley and Carl W. Baum
Dept. Electrical & Computer Engineering
303 Fluor Daniel Bldg.
Clemson University
Clemson, SC 29634

Abstract:

Research has been completed on the performance of mobile, distributed, spread-spectrum wireless communication networks. New network protocols have been designed, analyzed, and simulated. The protocols are adaptive in order to maintain efficiency in environments with time-varying interference and propagation conditions. Results have been developed and published for adaptive transmission, adaptive forwarding, channel access, and adaptive routing protocols.

Research Results:

Full descriptions of our research results can be obtained from our research publications listed in this report. The research was motivated by the need for adaptive protocols to provide energy-efficient, reliable communications in mobile wireless networks for tactical communications. Such networks experience frequent changes in topology and operating environment. The adaptive protocols developed and evaluated in this project include transmission, channel access, forwarding, and routing protocols. Analytical methods were employed where applicable, and OPNET-based simulations for frequency-hop (FH) and direct-sequence (DS) spread-spectrum networks were employed for performance evaluations for networks of the size and complexity for which analysis is not possible.

One of the topics of our research on this project was energy-based routing. In addition to accounting for the interference on the links in the network, our new routing protocol also accounts for estimated energy expenditures on the links and routes in the network. Routing is accomplished using least-resistance routing (LRR) with a metric that provides a measure of anticipated energy consumption for transmissions on a communication link. In one of the previous versions of LRR, the metric is based on a combination of the counts of errors and erasures for transmissions on a link. This metric is referred to as the EE metric, and it provides a link resistance that reflects the

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interference experienced by the receiving radio on that link. In the current research, LRR is used with a new energy metric (EN) that is an extension of the EE metric. The EN metric includes a measure of the energy needed for successful transmission on the link. This metric and the LRR protocol are integrated with the adaptive transmission protocol, and the performance of the new protocol suite is evaluated for a distributed FH network. Our results demonstrate that in FH networks that employ an adaptive transmission protocol, the new method for routing can adapt quickly to changes in interference and propagation conditions. We find that the LRR protocol with the EN metric works with the adaptive transmission protocol to improve the information throughput and energy efficiency of the network.

We have shown in previous research that it is necessary to couple physical-layer elements with network-level protocols in the design of a tactical wireless network. Our adaptive transmission protocols match the transmission parameters to changes in the characteristics of the links in the network, and the changes made in the transmission parameters must also be accounted for in the network protocols. In the research project we incorporated link-level adaptive transmission protocols into the network-level adaptive routing and forwarding protocols that are based on least-resistance routing.

Evaluation of the performance of network protocols necessitates the use of simulation. We have developed a new Gaussian approximation to model the effects of multiple-access interference on the acquisition performance of DS networks. The acquisition technique uses a matched filter to detect fixed-length packet headers. The approximation explicitly accounts for carrier phase drift and the effects of an automatic-gain-control amplifier. A method has been developed for selecting an acquisition threshold that works well in a wide range of channels. This acquisition model has been incorporated in our DS network simulations.

The choice of media access (MAC) protocol can have a dramatic effect on the performance of DS packet radio networks. We have investigated the use of multi-frequency-channel reservation-based protocols and found that they significantly outperform slotted Aloha and single-channel ready-to-send clear-to-send techniques, especially in conditions of high traffic. In the multi-frequency protocols, one frequency band is used for control traffic, and the others are used for data packets. The protocols support multicasting for the transmission of packet-radio-organization packets (PROPs). These channel access protocols have also been incorporated in our DS network simulations.

A multimedia MAC protocol has also been developed. The protocol has been specifically designed for half-duplex radios that employ DS signaling. The transmission of random-access traffic and PROPs is achieved by the protocol described above. Overlaying this protocol is a protocol for the support of virtual circuit connections. A form of local time slotting is employed so that individual radios can support multiple virtual circuit connections simultaneously. Virtual circuit data is transmitted periodically, and associated with each virtual circuit connection are periodically broadcast control packets containing channel access information. The content of the control packets is used by other radios to avoid contention. Components of the protocol include channel listening and pacing algorithms, channel selection algorithms, and algorithms for virtual circuit setup and termination. Simulation results show that the protocols provide reliable virtual circuit connections while maintaining high random-access throughput.

We have developed a protocol to be used in conjunction with least resistance routing that employs rules to check for route consistency. The protocol combines consistency checking with the use of timers that discard outdated routing information to reduce the frequency and the persistence of routing loops. It has been shown through simulation that the enhancements can significantly enhance the throughput of distributed DS networks with high mobility.

Publications:

A. R. Raghavan, C. W. Baum, and D. L. Noneaker, "Analysis of a serial acquisition scheme for unslotted distributed direct-sequence packet radio networks," *Proceedings of the IEEE 1998 International Conference on Communications,* (Atlanta, GA), pp. 35.5.1-5, June 1998.

A. R. Raghavan and C. W. Baum, "A new Gaussian approximation for analysis of a serial acquisition scheme in the presence of fading," *Proceedings of the 1998 IEEE International Symposium on Information Theory*, (Cambridge, MA), p. 243, August 1998.

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M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Tradeoffs in the design of routing metrics for frequency-hop wireless networks," *Proceedings of the 2000 IEEE Military Communications Conference*, (Los Angeles, CA), vol. 1, pp. 3.1.1-5 , October 2000.

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J. H. Gass, Jr., M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An adaptive-transmission protocol for frequency-hop wireless communication networks," to appear in *Wireless Networks*, vol. 7, no. 5, September 2001.

A. R. Raghavan, C. W. Baum, and D. L. Noneaker, "Analysis of a serial acquisition technique for direct-sequence packet-radio networks," to appear in the *IEEE Transactions on Vehicular Technology*.

R. T. Balaji and C. W. Baum, A multimedia MAC protocol for distributed DS mobile radio networks, to appear in the *Proceedings of the 2001 IEEE Military Communications Conference*, (Vienna, VA), Oct. 2001.

Personnel Supported:

Professor Michael Pursley
Associate Professor Carl Baum
Assistant Professor Daniel Noneaker
Assistant Professor Harlan Russell

Graduate Research Assistant Arvind Raghavvan
Graduate Research Assistant Jeffrey Wysocarski
Graduate Research Assistant Rayadurgam Balaji
Graduate Research Assistant Clint Wilkins
Graduate Research Assistant Frederick Block
Graduate Research Assistant Jason Ellenburg